

Proceedings of the Second Annual LHCP  
ATL-UPGRADE-PROC-2014-004  
September 18, 2014

## The ATLAS upgrade program

CLAUDIA GEMME

*On behalf of the ATLAS Collaboration,  
Istituto Nazionale di Fisica Nucleare, Genova, Italy*

### ABSTRACT

After the first successful LHC run in 2010-2012, plans are actively advancing for a series of upgrades leading eventually to annual integrated luminosities about ten times the current design after 10 years. The larger integrated luminosity will allow to perform precise measurements of the just discovered Higgs boson and to continue searching for new physics beyond the Standard Model. Coping with the high instantaneous and integrated luminosity will be a great challenge for the ATLAS detector and will require changes in most of the subsystems, especially those at low radii or large pseudorapidity, as well as in its trigger architecture. Plans to consolidate and, whenever possible, to improve the physics performance of the current detector over the next decade are summarized in this paper.

### PRESENTED AT

The Second Annual Conference  
on Large Hadron Collider Physics  
Columbia University, New York, U.S.A  
June 2-7, 2014

# 1 Introduction

ATLAS [1] is a general-purpose experiment designed to explore the  $pp$  collisions at the CERN Large Hadron Collider (LHC) [2] at center of mass energies up to  $\sqrt{s} = 14$  TeV and a maximum peak luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ .

ATLAS has been successfully operating in 2010-2012, collecting collision data at  $\sqrt{s} = 7$  and 8 TeV, recording an integrated luminosity of  $\sim 25 \text{ fb}^{-1}$  with a peak luminosity of  $7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ . The discovery [3, 4] of a 126 GeV Higgs boson in 2012 is the greatest, even if not the unique, achievement allowing to identify the last piece of the highly successful Standard Model (SM). In the next years, LHC will undergo a series of upgrades leading ultimately to five-fold increase of the instantaneous luminosity with leveling according to the High-Luminosity LHC (HL-LHC) project. The goal is to extend the dataset from about  $300 \text{ fb}^{-1}$ , expected to be collected by the end of the LHC run (in 2022), to  $3000 \text{ fb}^{-1}$  by 2035. The foreseen higher luminosity at the HL-LHC is a great challenge for ATLAS. Meeting it will require significant but gradual detector optimizations, changes and improvements, which are the subject of these proceedings.

## 2 LHC and ATLAS Upgrade Plans

The main motivation for the LHC upgrades is to extend and improve the physics program. The capability to maintain an optimal trigger system as the luminosity increases beyond its nominal design value is crucial for the physics reaches and requires a strong reduction of the main source of backgrounds, as jets mimicking electrons in the calorimeters and misidentified muons in the forward spectrometer. Otherwise, increased trigger threshold cuts would have to be deployed to control the rates, reducing significantly the signal efficiency. As an example, the acceptance for muons from  $t\bar{t}$ , WH and SUSY processes as a function of the true muon  $p_T$  is shown in Figure 1, where an increase in threshold from 20 GeV to 30 GeV results in a reduction in signal acceptance ranging from 1.3 to 1.8.

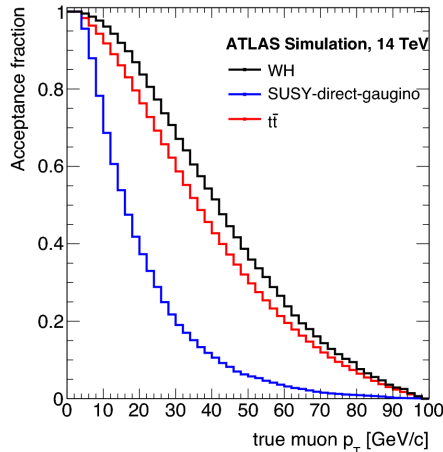


Figure 1: Acceptance of muons from  $t\bar{t}$ , WH and SUSY processes as a function of true muon momentum.

A major focus of the physics program is on the Higgs boson [5]. With larger luminosity, it will be possible to make precision measurements of the Higgs boson properties, in particular its couplings to fermions and bosons, its rare decays and its self-couplings. As an example, Fig. 2(a) shows the dimuon invariant mass for the measurement of the  $H \rightarrow \mu\mu$  channel: with an integrated luminosity of  $3000 \text{ fb}^{-1}$ , this rare channel can be observed. The relative uncertainties on the total signal strength for some Higgs decay modes for the 300 and  $3000 \text{ fb}^{-1}$  luminosities are reported in Fig. 2(b). New physics searches, beyond the Standard Model, will continue in SUSY or other exotic physics scenarios.  $WW$  scattering measurements will also be essential amongst the electroweak symmetry breaking mechanism measurements.

The harsher radiation environment and higher detector occupancies at the HL-LHC imply major changes to most of the ATLAS systems, specially those at low radii and large pseudorapidity. A general guideline

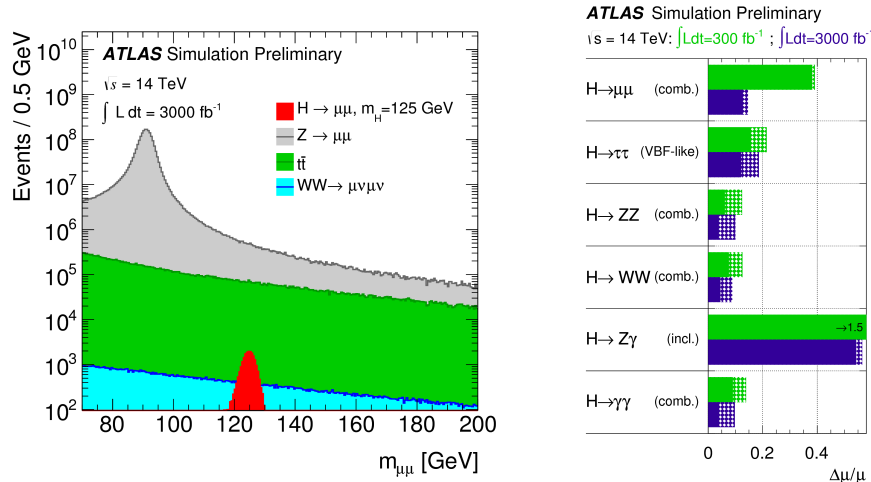


Figure 2: (a) Distribution of the dimuon invariant mass of the signal and background processes generated for  $\sqrt{s} = 14$  TeV and  $L = 3000 \text{ fb}^{-1}$ . (b) Relative uncertainty on the total signal strength for all Higgs final states in the different experimental categories used in the combination, assuming a SM Higgs Boson with a mass of 125 GeV. The hashed areas indicate the increase of the estimated error due to current theory systematic uncertainties.

for these changes is maintaining the same or improve the detector performance measured at the LHC. The higher event rates and event sizes will be a challenge for the trigger and data acquisition (DAQ) systems, which will require a significant extension of their capacity.

The ATLAS upgrade will be gradual and flexible to accommodate a possible evolution of LHC operational parameters and indications of new physics signals. It is planned in three phases, which correspond to the three long technical shutdowns of the LHC towards the HL-LHC.

### 3 Phase-0 upgrades

The repair of the splices in the main accelerator during the long shutdown in 2013-2014 (LS1) will allow the LHC to continue its operation close to its design parameters with a center of mass energy  $\sqrt{s} = 13$ -14 TeV, 25 ns bunch spacing and peak luminosities  $\sim 1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , and deliver an integrated luminosity  $\geq 50 \text{ fb}^{-1}$  before the following shutdown.

ATLAS has used the shutdown period (Phase-0) for detector consolidation works, including a new Inner Detector (ID) cooling system, a new diamond beam monitor, the replacement of the Pixel internal services, new power supplies for the calorimeter, an improved coverage of the Muon Spectrometer (MS) between the barrel and the end-cap regions and a new beam pipe, in the central and forward region. But the main upgrade activity in Phase-0 is the installation of a new barrel layer in the Pixel detector. The Insertable B-Layer (IBL) [6] is an additional, 4<sup>th</sup> pixel layer, that has been built around the new central beam pipe and then slipped inside the present Pixel detector in situ. The IBL is therefore placed between the actual innermost pixel layer (the B-layer) and the beam pipe, at a sensor average radius of 33 mm (50.5 mm is the radius of the B-layer). To make the installation of the IBL possible, the new Be beam pipe radius is reduced by 4 mm radius ( $r=29 \text{ mm} \rightarrow r=25 \text{ mm}$ ).

IBL consists of 14 pixel staves surrounding the beam-pipe. Each carbon-fibre stave carries and provides cooling to 32 read-out chips, which are bump-bonded to silicon sensors. The pseudo-rapidity coverage extends to  $|\eta| < 3$ . Two types of sensors are used: planar n-in-n sensors, similar to the present Pixel detector, and 3D silicon sensors installed, for the first time, in a tracking detector. To cope with a larger fluence and peak luminosity, higher hit rate and occupancy, a new generation of read-out chip, FE-I4, has been developed using a new architecture, IBM 130 nm CMOS process manufacturing resulting in a smaller

pixel size ( $50 \times 250 \mu\text{m}^2$ ). 18 staves have been qualified and out of them the best 14 have been chosen to be assembled in the IBL detector. Fig. 3 shows the longitudinal distribution of the bad pixel fraction for the produced staves. The new detector has been installed inside ATLAS in May 2014 and commissioning is ongoing. So far it is fully functional with only 0.1% of the channels disabled.

IBL will help to preserve the tracking performance at high luminosity when the B-layer will suffer from radiation damage and high pile-up occupancies. Moreover, it will compensate for defects (irreparable failures of modules) in the existing detector, assuring tracking robustness. Given the closer position to the impact point and the smaller pixel size, IBL will also improve the vertex resolution, secondary vertex finding and  $b$ -tagging, hence extending the reach of the physics analysis.

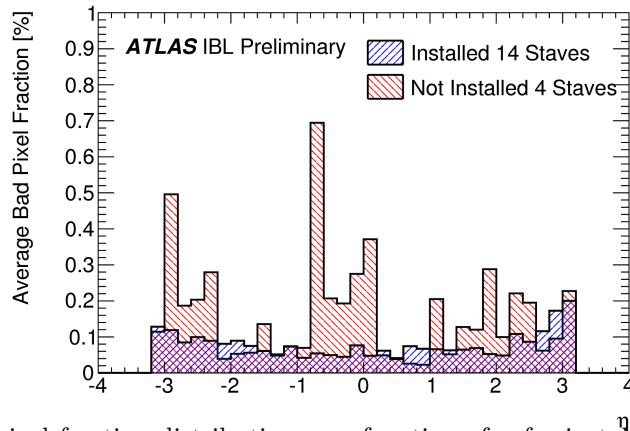


Figure 3: Average bad pixel fraction distribution as a function of  $\eta$  for installed (blue) and not installed (red) production staves.

## 4 Phase-I upgrades

A second shutdown (LS2) is being planned in 2018 to integrate the Linac4 into the injector complex, to increase the energy of the PS Booster to reduce the beam emittance, and to upgrade the collider collimation system. When data taking resumes in 2020, the peak luminosity is expected to reach  $\sim 2 - 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  corresponding to 55 to 80 interactions per crossing (pile-up) with 25 ns bunch spacing, well beyond the initial design goals. LHC is planning to deliver an integrated luminosity of  $\sim 300 \text{ fb}^{-1}$  before the next shutdown, thus extending the reach for discovery of new physics and the ability to study new phenomena and states. In this long shutdown, so-called Phase-I, ATLAS proposes the installation of new muon Small Wheels and several updates for the trigger system (Fast TracKer, Calorimetric and topological triggers) to handle luminosities well beyond the nominal values. Detailed plans are described in Ref. [7].

**New Small Wheels.** At high luminosity the performance of the muon tracking chambers (in particular in the end-cap region) degrades with the expected increase of cavern background rate. Moreover, in the current detector, the Level-1 muon trigger in the end-cap region is based on track segments in the intermediate muon station located after the end-cap toroid magnet. An analysis of 2012 data demonstrates, see Fig. 4(a), that approximately 90% of the muon triggers in the end-caps are fake or background, dominated by low energy particles, mainly protons, generated in the material located between the Small Wheel and the middle station, hitting the end-cap trigger chambers at an angle similar to that of real high  $p_T$  muons. Therefore, to face with the large expected rates of the LHC upgrades, a replacement of the first endcap station of the Muon Spectrometer, the New Small Wheel (NSW), is proposed [8]. The NSW must ensure efficient tracking at high particle rate (up to  $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ) and larger  $|\eta|$ , with position resolution of  $< 100 \mu\text{m}$ . Furthermore, unlike the present layer, the NSW will be integrated into the Level-1 trigger, thus helping in rejecting background by selecting tracks coming from the primary interaction and matched with the most external layers of the muon spectrometer, see Fig. 4(b).

The NSW will have two chamber technologies, one primarily devoted to the Level-1 trigger function

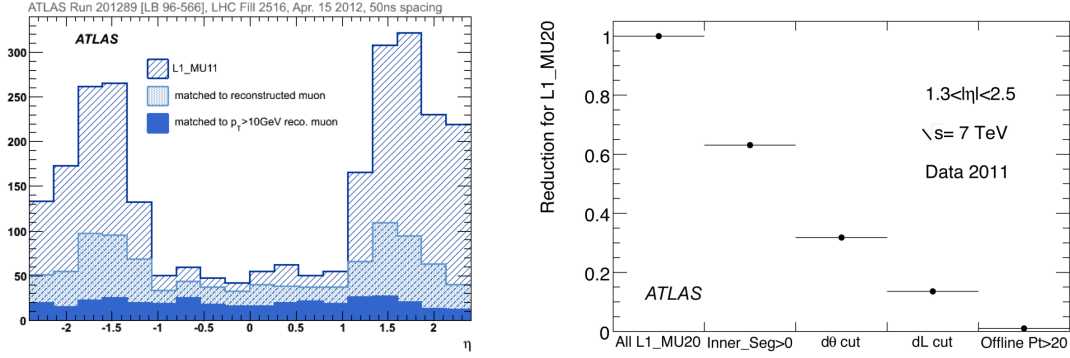


Figure 4:  $\eta$  distribution of Level-1 muon signal L1\_MU11 with the distribution of the subset with matched muon candidate to an offline well reconstructed muon and offline reconstructed muons with  $p_T > 10$  GeV. (b) Expected reduction of L1\_MU20 rate simulated using collision data by successive applications of requirements on the small wheel segments: to have a segment in the Small Wheel (Inner\_Seg > 0), that it is pointing to the primary ( $d\theta$  cut) and matched to the external muon chamber segment (dL cut).

(small-strip Thin Gap Chambers, sTGC) and one dedicated to precision tracking (MicroMegas detectors, MM). The sTGC are primarily deployed for triggering given their single bunch crossing identification capability. The MM detectors have exceptional precision tracking capabilities due to their small gap (5 mm) and strip pitch (approximately 0.5 mm). Such a precision is crucial to maintain the current ATLAS muon momentum resolution in the high background environment of the upgraded LHC.

**Level-1 LAr Calorimeter Electronics.** Also the calorimetric trigger will have an upgrade [9] in Phase-1: the objective of this upgrade is to provide higher-granularity, higher-resolution and longitudinal shower information from the calorimeter to the Level-1 trigger processors. The 10-fold increase in granularity will improve the trigger energy resolution and efficiency for selecting electrons, photons,  $\tau$  leptons, jets and missing transverse momentum, while enhancing discrimination against backgrounds and fakes. Fig. 5 shows how the finer granularity enables a more sophisticated rejection of jet backgrounds than in the current system through the use of shower shape variables: in the (a) distribution the discriminating power of one variable is shown, while (b) shows the Level-1 trigger rate reduction when exploiting it.

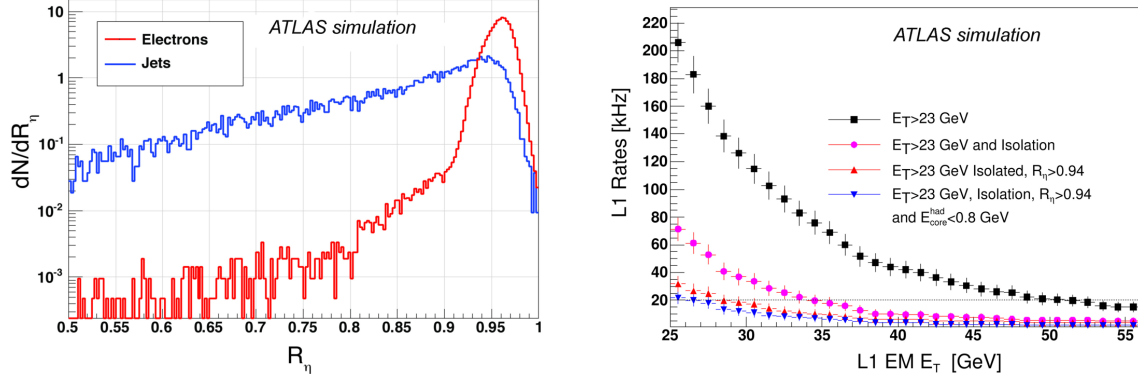


Figure 5: Monte Carlo simulations: (a) Distribution of the  $R_\eta$  parameter for electrons and jets, defined as the ratio of the energy in the 3x2 over the energy in the 7x2 clusters of the 2nd layer of the EM calorimeter. (b) Expected Level-1 rates for different algorithms and conditions: the current Level-1 rate for non-isolated EM objects, for isolated EM objects, for isolated EM objects after a shower shape  $R_\eta > 0.94$  cut applied.

**Fast Track Trigger (FTK).** The Fast TracKer Trigger [10] will perform the track finding and fitting on-line using dedicated massive parallel processing, which makes it extremely faster, instead of the Level-2

software farm as in the current trigger schema. FTK will then provide the track parameters with resolution close to the offline one shortly after the start of the Level-2 processing thus releasing extra resources for more advanced selection algorithms, which ultimately could improve the performances of the tracking-based filter algorithms such as the  $b$ -tagging and  $\tau$  trigger. While the full geometrical coverage for full Phase-I pile-up is foreseen after the 2018 shutdown, a progressive coverage and commissioning will start already in 2015.

**Trigger and Data Acquisition.** New calorimeter feature extraction processors and a new processor for the muon signals will produce object quantities that can be combined with each other and other signals in a new topological processor. The Data Acquisition and the High-Level Trigger (HLT) processing farm will be upgraded to allow full calorimetry information and the outputs of the FTK system to be read out and processed. A detailed description of this upgrade can be found in [11].

## 5 Phase-II upgrades

The Phase-I upgrades are designed to be fully forward-compatible with the physics program of the high luminosity HL-LHC (Phase-II), when the instantaneous luminosity should reach  $\sim 5 - 7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , up to 200 interactions per crossing (pile-up) and a total integrated luminosity of  $3000 \text{ fb}^{-1}$ . A third 36-months long shutdown (LS3) in 2023-25 will be necessary to upgrade the accelerator to this ultimate operation mode. ATLAS is being planning major updates in all its subsystems and trigger architecture [12].

**New Inner Tracker.** The present ATLAS Inner tracker will have several limitations in Phase-II when up to 200 pile-up events per bunch crossing are expected. The gas-based TRT (Transition Radiation Tracker, the outermost system of the the ATLAS Inner Detector) has a limit due to instantaneous luminosity because of very high occupancy. The functionality of the silicon-based parts of the tracker will be deteriorated due to the total radiation dose affecting both sensors and read-out electronics and also by the instantaneous luminosity, too high for the present limited band-width. Because of all these factors, the entire Inner Detector will be replaced with a new, all-silicon Inner Tracker (ITk) with pixel sensors at the inner radii surrounded by microstrip sensors. The current baseline design of the ITk, with a layout similar to the present detector, has in the central region sensors arranged in cylinders, with 4 pixel layers followed by 3 short-strip layers then 2 long-strip layers; the forward regions will be covered by 6 pixel disks and 7 strip disks. Other layouts are currently under study, even extending the coverage at larger pseudo-rapidity. Some characteristics of the performance of this layout are listed: robust tracking with at least 11 hits/track for  $|\eta| < 2.5$ , channel occupancy  $< 1\%$  for pile-up up to 200 (Fig. 6(a)), reduced material (factor 5 for  $|\eta| < 1$ ) with respect to current ID. The performance of  $b$ -tagging, in particular for high energy jets, depends critically on the rate of fake tracks, and on the two-track resolution. Using current algorithms, the light jet rejection of the new tracker at high pile-up is found (Fig. 6(b)) to be as good as that for the current ID (including the IBL) at zero pile-up.

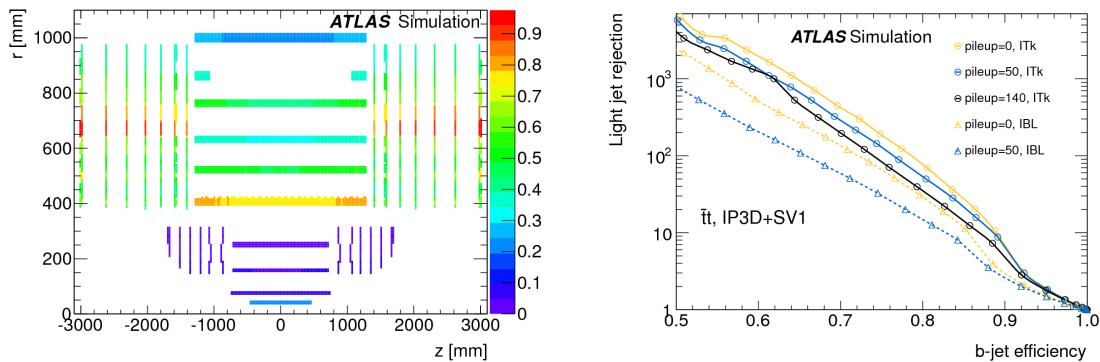


Figure 6: (a) Channel occupancies (in percent) with 200 pile-up events. (b) Performance of  $b$ -tagging in  $t\bar{t}$  events, for a range of pile-up levels for the proposed Phase-II Tracker layout in comparison with ID+IBL.

**Trigger.** A new trigger architecture is being developed that is compatible with the constraints imposed by the detector and provides a flexible trigger with the potential to deliver the required performance. As currently envisaged, the baseline design for the Phase-II Trigger, schematically sketched in Fig. 7, foresees a split Level-0/Level-1 hardware trigger with a total level-1 accept rate of 200 kHz and total latency of 20  $\mu$ s. The Level-0 trigger would distribute the Level-0 accept at a rate of at least 500 kHz within a latency of 6  $\mu$ s. The Phase-II Level-0 trigger is functionally the same as the Phase-I Level-1 system, based only on calorimetric and muon inputs. The Level-0 accept is generated by the central trigger system which incorporates topological triggering capability. The Level-1 system will reduce the rate to 200 kHz within an additional latency of 14  $\mu$ s. This reduction will be accomplished by the introduction of track information within a Region-of-Interest (RoI), full calorimeter granularity within the same RoI and the introduction of a refined muon selection based on the use of the MDT information. All the trigger electronics of the calorimeters and muon spectrometer will need to be upgraded to face these trigger rates. Moreover the calorimeter electronics will also undergo changes to allow 40 MHz read-out of all the data without on-detector buffering.

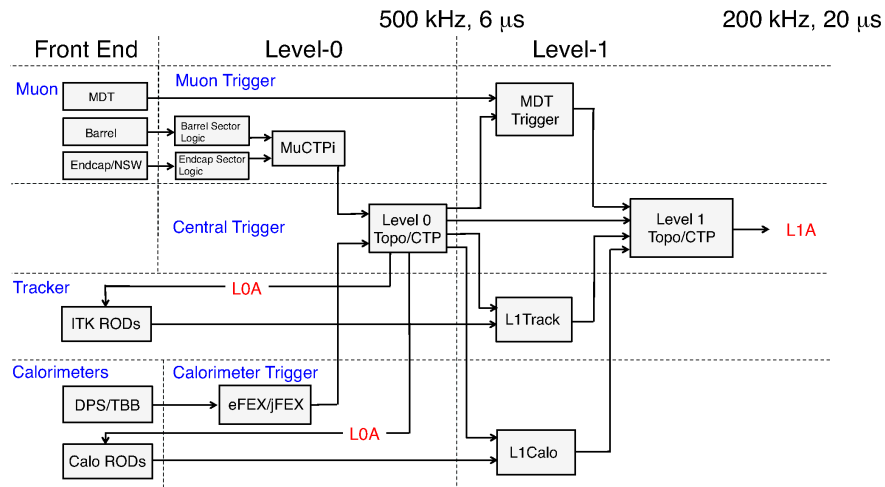


Figure 7: A block diagram of the architecture of the split Level-0/Level-1 hardware trigger proposed for the Phase-II upgrade.

## 6 Conclusions

A coherent overall upgrade program for ATLAS from Phase-0 through Phase-II has been planned to allow ATLAS to fully exploit the LHC energy and instantaneous luminosity at up to 5-7 times the design value. Phase-0 is successfully concluded, while Technical Design Reports have been prepared for the Phase-I projects as well as the Letter of Intent for Phase-II. The planned approach is gradual and accommodates flexibility which can profit from running and indications from physics results.

## References

- [1] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider,” J. Instr. **3**, S08003 (2008).
- [2] L. Evans and P. Bryant, “LHC Machine,” J. Instr. **3**, S0801 (2008).
- [3] ATLAS Collaboration, Phys.Lett. B716 (2012) 1-29.
- [4] CMS Collaboration, Phys. Lett. B 710 (2012) 26.

- [5] ATLAS Collaboration, ATL-PHYS-PUB-2013-014.
- [6] ATLAS IBL Collaboration, “Insertable B-Layer, Technical Design Report,” CERN-LHCC-2010-013.
- [7] ATLAS Collaboration, “Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment,” CERN-LHCC-2011-012, LHCC-I-020.
- [8] ATLAS NSW Collaboration, “New Small Wheel Technical Design Report,” CERN-LHCC-2013-006.
- [9] ATLAS Collaboration, “ATLAS Liquid Argon Calorimeter Phase-I Upgrade Technical Design Report,” CERN-LHCC-2013-017.
- [10] ATLAS Collaboration, “Fast TracKer (FTK) Technical Design Report,” CERN-LHCC-2013-007.
- [11] ATLAS Collaboration, “Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System,” CERN-LHCC-2013-018.
- [12] ATLAS Collaboration, “Letter of Intent for the Phase-II Upgrade of the ATLAS Experiment,” CERN-LHCC-2012-022, LHCC-I-023.